ASTRONOMY METHODS

A Physical Approach to Astronomical Observations

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CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK
40 West 20th Street, New York, NY 10011-4211, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

http://www.cambridge.org

First published 2004

Printed in the United Kingdom at the University Press, Cambridge

Typefaces Times 11/14 pt. and Univers *System* LaTeX 2_ε [TB]

A catalog record for this book is available from the British Library

Library of Congress Cataloging in Publication data
Bradt, Hale, 1930–
Astronomy methods: a physical approach to astronomical observations / Hale Bradt.
p. cm.
Includes bibliographical references and index.
ISBN 0 521 36440 X – ISBN 0 521 53551 4 (pbk.)
1. Astronomy. I. Title.
QB45.2.B73 2003 520–dc21 2002041703

ISBN 0 521 36440 X hardback
ISBN 0 521 535514 paperback

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Astronomy through the centuries

What we learn in this chapter

Celestial measurements reaching back 3000 years or more were carried out in many cultures worldwide. **Early astronomers** in Greece deduced important conclusions about the nature of the **earth** and the **solar system**. Modern astronomy began in the **renaissance** with the observations of **Tycho Brahe** and **Galileo** and the theoretical work of **Kepler** and **Newton**. The progress of our knowledge of the sky may be traced through a series of **major discoveries** which often follow the development of new **technologies** such as the **telescope**, **computers**, and **space observatories.** Astronomy is now carried out across the entire electromagnetic spectrum from the **radio** to the **gamma ray** (see cover illustrations) as well as with **cosmic rays**, **neutrinos,** and **gravitational waves**. The mutual dependence of **theory** and **observation** has led to major advances in the understanding of a wide diversity of celestial objects such as **stars**, **supernova remnants**, **galaxies,** and the **universe** itself. Current observations reveal important phenomena that are not understood. The promise of **new fundamental discoveries** remains high.

1.1 Introduction

This introductory chapter provides a brief sketch of the history of astronomy with emphasis upon some pivotal ideas and discoveries. The ideas presented here are covered more systematically in subsequent chapters of this or subsequent planned volumes.

1.2 Early development of astronomy

First astronomers

The rhythmic motions of the stars, the planets, and the sun in the sky have fascinated humankind from the earliest of times. The motions were given religious significance

Figure 1.1. Stonehenge, an early astronomical observatory used for tracking the sun and moon in their seasonal excursions. [© Crown copyright, NMR]

and were useful agricultural indicators. The sun's motion from south to north and back again marked the times of planting and harvesting. The annual motion of the sun against the background of the much more distant stars could also be followed and recorded, as could the motions of the moon and planets. This made possible predictions of the future motions of the sun and moon. Successful forecasters of the dramatic eclipses of the sun seemed to be in touch with the deities.

The periodic motions of the sun and moon were noted and described with calendars as early as the thirteenth century BCE in China. Surviving physical structures appear to be related to the motions of celestial bodies. Notable are an eighth century BCE sundial in Egypt and the assemblage of large stones at Stonehenge in England dating from about 2000 BCE (Fig. 1)[1]. The Babylonians and Assyrians in the Middle East are known to have been active astronomers in the several centuries BCE (The designations BCE "before common era" and CE "common era" are equivalent to BC and AD respectively.)

[1] In an attempt to minimize redundant numbers in the text, we omit the chapter designation in references to figures within the chapter in which the figure occurs, e.g. "Fig. 2". For references to figures in another chapter, say, Chapter 3, the reference is the conventional format "Fig. 3.2". Problem, equation, and section references are treated similarly. Equations are usually referenced in the text as a number within parentheses without the prefix "Eq.", for example: "as shown in (10)" for equations within the chapter, or "given in (5.10)" for Eq. 10 of Chapter 5.

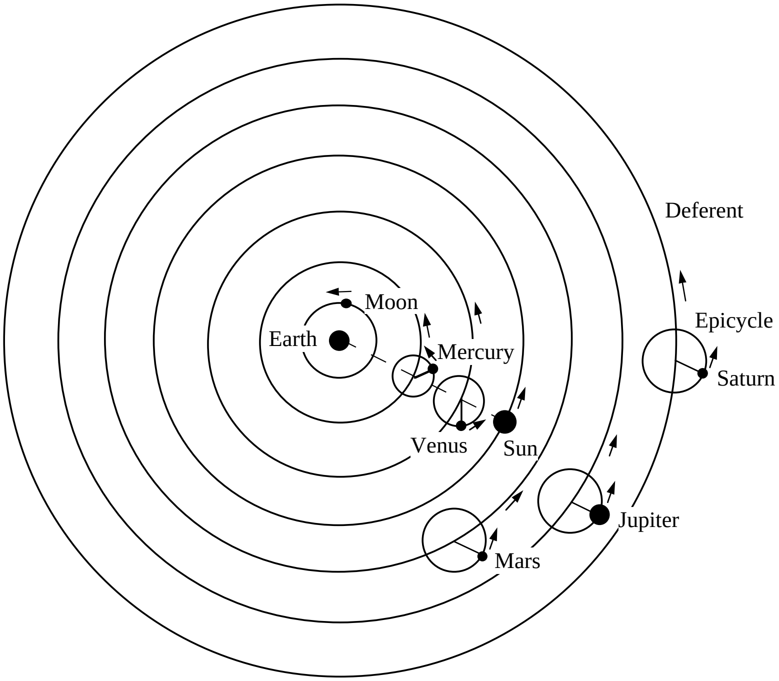
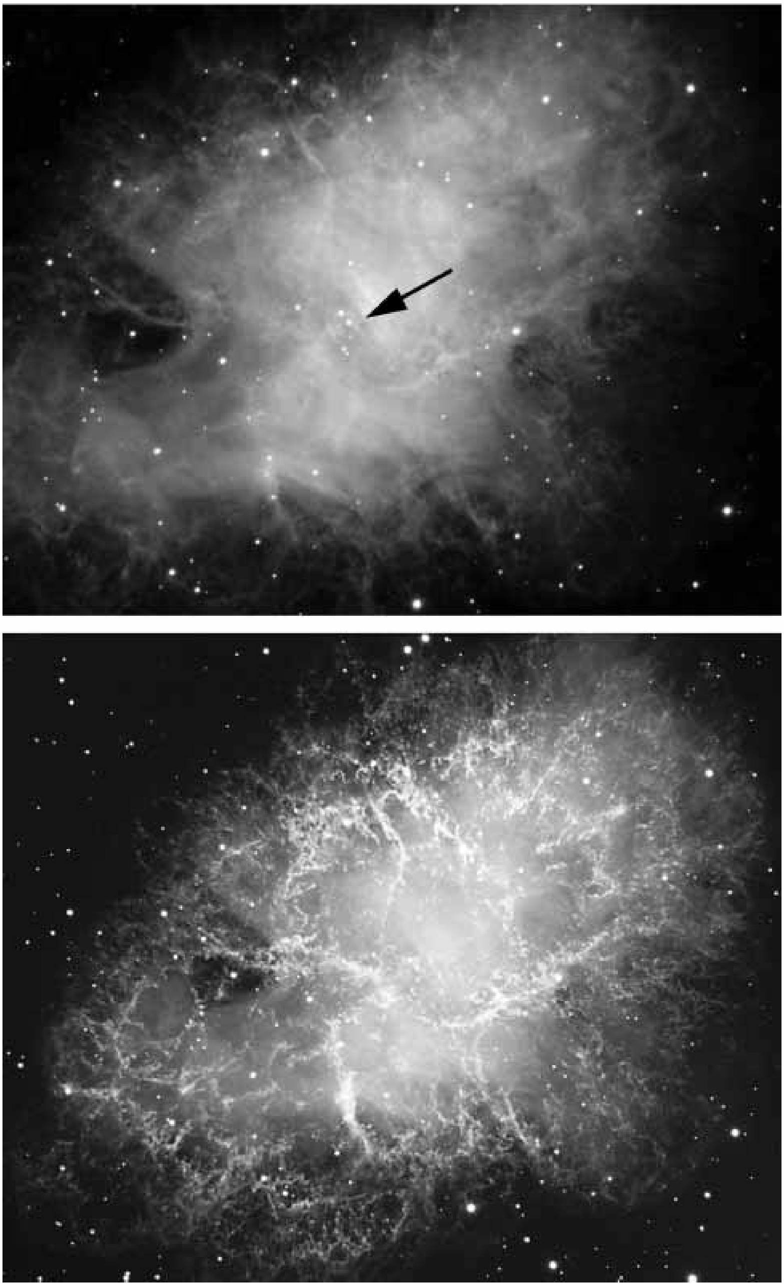


Figure 1.2. Ptolemaic system, not drawn to scale. The earth is at the center, the moon and sun follow circular paths and the planets follow (small) circular orbits (epicycles) the centers of which move regularly along large circular orbits known as deferents. Elliptical orbits are taken into account by offsetting slightly the centers of the deferents and also the earth itself from a geometrical "center".

Astronomy flourished under Greek culture (∼600 BCE to ∼400 CE) with important contributions by Aristotle, Aristarchus of Samos, Hipparchus, Ptolemy, and others. The Greek astronomers deduced important characteristics of the solar system. For example, Aristotle (384–322 BCE) argued from observations that the earth is spherical, and Aristarchus (310–230 BCE) made measurements to obtain the sizes and distances of the sun and moon relative to the size of the earth. Ptolemy (∼140 CE) developed a complicated earth-centered model (Fig. 2) for the solar system which predicted fairly well the complicated motions of the planets as viewed from the earth.

The advance of astronomy in Europe faltered during the following 13 centuries. Nevertheless the sky continued to be observed in many cultures, e.g., the Hindu, Arabian, and Oriental. The sudden appearances of bright new and temporary "guest" stars in the sky were noted by the Chinese, Japanese, Koreans, Arabs, and Europeans. The most famous of all such objects, the Crab supernova, was recorded in 1054 by Chinese and Japanese astronomers. It is now a beautiful diffuse nebula in the sky (Fig. 3). The Mayan culture of Central America independently developed



(a)

(b)

Figure 1.3. Crab nebula, the remnant of a supernova explosion observed in 1054 CE. The neutron-star pulsar is indicated (arrow). The filters used for the two photos stress (a) the blue diffuse synchrotron radiation and the pulsar and (b) the strong filamentary structure that glows red from hydrogen transitions. The scales of the two photos are slightly different. The Crab is about 4′ in extent and ~6000 LY distant. The orientation is north up and east to the left – as if you were looking at the sky while lying on your back with your head to the north; this is the standard astronomical convention. [(a) Jay Gallagher (U. Wisconsin)/WIYN/NOAO/NSF.; (b) FORS Team, VLT, ESO]

strong astronomical traditions, including the creation of a sophisticated calendar that could be used, for example, to predict the positions of Venus.

Renaissance

The Renaissance period in Europe brought about great advances in many intellectual fields including astronomy. The Polish monk Nicholaus Copernicus (1473–1543) proposed the solar-centered model of the planetary system. The Dane Tycho Brahe (1546–1601, Fig. 4) used elegant mechanical devices to measure planetary positions to a precision of $\sim 1'$ (1 arcminute)[1] and, over many years, recorded the daily positions of the sun, moon, and planets.

The German Johannes Kepler (1571–1630, Fig. 4), Brahe's assistant for a time, had substantial mathematical skills and attempted to find a mathematical model that would match Brahe's data. After much effort, he found that the apparent motions of Mars in the sky could be described simply if Mars' orbit about the sun is taken to be an ellipse. He summarized his work with the three laws now known as Kepler's laws of planetary motion. They are: (*i*) each planet moves along an elliptical path with the sun at one focus of the ellipse, (*ii*) the line joining the sun and a planet sweeps out equal areas in equal intervals of time, and (*iii*) the squares of the periods P (of rotation about the sun) of the several planets are proportional to the cubes of the semimajor axes a of their respective elliptical tracks,

$$P^2 \propto a^3 \qquad \text{(Kepler's third law)} \qquad (1.1)$$

This formulation laid the foundation for the gravitational interpretation of the motions by Newton in the next century.

Galileo Galilei (1564–1642, Fig. 4), a contemporary of Kepler and an Italian, carried out mechanical experiments and articulated the *law of inertia* which holds that the state of constant motion is as natural as that of a body at rest. He adopted the Copernican theory of the planets, and ran afoul of the church authorities who declared the theory to be "false and absurd". His book, *Dialog on the Two Great World Systems* published in 1632, played a significant role in the acceptance of the Copernican view of the solar system. Galileo was the first to make extensive use of the *telescope*, beginning in 1609.

The telescope was an epic technical advance in astronomy because, in effect, it enlarged the eye; it could collect all the light impinging on the objective lens and direct it into the observer's eye. Since the objective lens was much larger than the lens of the eye, more light could be collected in a given time and fainter objects could be seen. The associated magnification allowed fine details to be resolved. Galileo was the first to detect the satellites (moons) of Jupiter and to determine

[1] The measures of angle are degree ($^\circ$), arcmin ($'$), and arcsec ($''$) where $60'' = 1'$ and $60' = 1^\circ$.

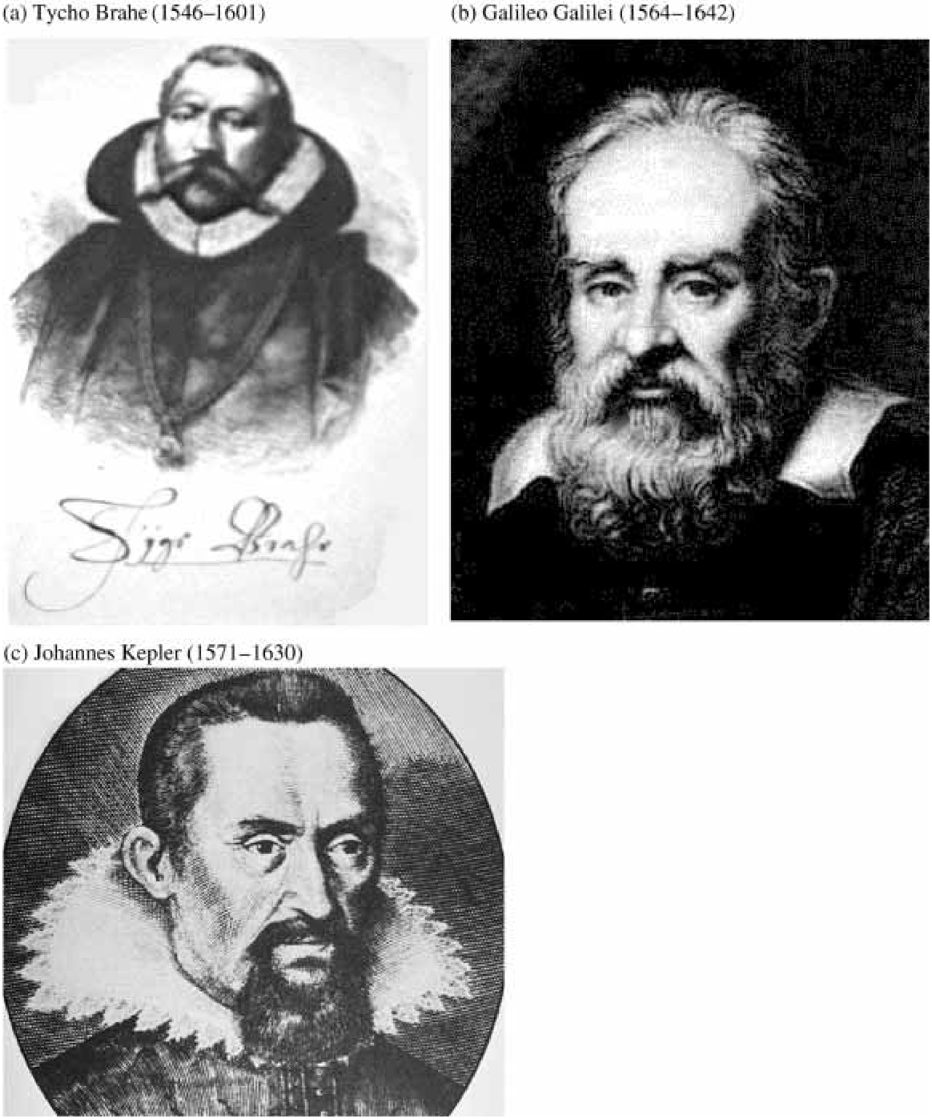


Figure 1.4. The three astronomers who pioneered modern astronomy. [(a) Tycho Brahe's Glada Vänner; (b) portrait by Justus Sustermans; (c) Johannes Kepler Gesammelte Werke, C. H. Beck, 1937. All are on internet: "Astronomy Picture of the Day", NASA/GSFC and Michigan Tech U.]

their orbital periods. He showed that the heavens were not perfect and immutable; the earth's moon was found to have a very irregular surface and the sun was found to have dark "imperfections", now known as *sunspots*.

The Englishman Isaac Newton (1643–1727; Gregorian calendar) was born 13 years after the death of Kepler and almost exactly one year after Galileo died.

His study of mechanics led to three laws, *Newton's laws*, which are stated here in contemporary terms: (*i*) the vector momentum $\boldsymbol{p} = m\boldsymbol{v}$ of a body of mass m moving with velocity $\boldsymbol{v}$ is conserved in the absence of an applied force[1] (this is a restatement of Galileo's law of inertia), (*ii*) a force applied to a body brings about a change of momentum,

$$\boldsymbol{F} = \frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} \qquad \text{(Newton's second law)} \qquad (1.2)$$

and (*iii*) the force $\boldsymbol{F}_{1,2}$ on one body due to second body is matched by an opposing force of equal magnitude $\boldsymbol{F}_{2,1}$ on the second body due to the first,

$$\boldsymbol{F}_{1,2} = -\boldsymbol{F}_{2,1} \qquad \text{(Newton's third law)} \qquad (1.3)$$

These laws are the bases of *Newtonian mechanics* which remains the essence of much modern mechanical theory and practice. It fails when the speeds of the bodies approach the speed of light and on atomic scales.

Newton was able to show that a *gravitational force* of a particular kind described perfectly the planetary motions described by Kepler. This force is an attractive gravitational force $\boldsymbol{F}$ between two bodies that depends proportionally upon the masses (m_1, m_2) and inversely with the squared distance r^2 between them,

$$\boldsymbol{F} \propto -\frac{m_1 m_2}{r^2}\hat{\boldsymbol{r}} \qquad \text{(Newton's law of gravitation)} \qquad (1.4)$$

where $\hat{\mathbf{r}}$ is the unit vector along the line connecting the two bodies. Such a force leads directly to the elliptical orbits, to the speeds of motion in the planetary orbit, and to the variation of period with semimajor axis described by Kepler's three laws. Thus, all the celestial motions of the earth, moon, and sun could be explained with a single underlying force. This understanding of the role of gravity together with the invention of the telescope set astronomy solidly on a path of quantitative measurements and physical interpretation, i.e., *astrophysics*.

1.3 Technology revolution

Telescopes, photography, electronics, and computers

The study of the sky continued with the development of larger and larger telescopes. Generally these were refractive instruments wherein the light passes through the lenses, as in a pair of binoculars. The glass refracts the different colors of light slightly differently (*chromatic aberration*) so that perfect focusing is difficult to attain. This led to reflecting telescopes that make use of curved mirrors. In this case, all wavelengths impinging at a position of the mirror from a given angle are

[1] We use italic boldface characters to signify vector quantities and the hat symbol to indicate unit vectors.

reflected in the same direction. The 5-m diameter mirror of the large telescope on Palomar Mountain in California (long known as the “200 inch”) was completed in 1949. It was the world’s largest telescope for many years. In the 1960s and 1970s, several 4-m diameter telescopes were built as was a 6-m instrument in the Soviet Union. At this writing, the two Keck 10-m telescopes in Hawaii are the largest, but other large telescopes are not far behind. New technologies which allow telescopes to compensate for the blurring of starlight by the earth’s atmosphere are now coming on line.

Photography was an epochal development for astronomy in the nineteenth century. Before this, the faintest object detectable was limited by the number of *photons* (the quanta of light) that could be collected in the integration time of the eye, $\sim$30 ms (millisecond) to $\sim$250 ms if dark adapted. If a piece of film is placed at the focus of a telescope, the photons can be collected for periods up to and exceeding 1 hour. This allowed the detection of objects many orders of magnitude fainter than could be seen by eye. A photograph could record not only an image of the sky, but also the *spectrum* of a celestial object. The latter shows the distribution of energy as a function of wavelength or frequency. The light from the object is dispersed into its constituent colors with a prism or grating before being imaged onto the film. Large telescopes together with photography and spectroscopy greatly enlarge the domains of quantitative measurements available to astronomers.

Since the mid-twentieth century, more sensitive electronic detection devices have come into use. Examples are the *photomultiplier tube*, the *image intensifier*, and more recently, the *charge-coupled detector* (CCD). Computers have come into wide use for the control of the telescope pointing and for analysis of the data during and after the observation. The greatly increased efficiencies of data collection and of analysis capability go hand in hand in increasing the effectiveness of the astronomer and his or her ability to study fainter and more distant objects, to obtain spectra of many objects simultaneously, or to measure bright sources with extremely high time resolution. In the latter case, changes of x-ray intensity on sub-millisecond time scales probe the swirling of ionized matter around neutron stars and black holes.

Non-optical astronomy

Electromagnetic radiation at radio frequencies was discovered by Heinrich Hertz in 1888. This eventually led to the discovery of radio emission from the sky by Carl Jansky in 1931. This opened up the field of *radio astronomy*, an entirely new domain of astronomy that has turned out to be as rich as conventional optical astronomy. Entirely new phenomena have been discovered and studied. Examples are the distant *quasars* (described below) and the neutral hydrogen gas that permeates interstellar space. The invention of the maser and the use of supercooled detectors have greatly increased the sensitivity and frequency resolution of radio telescopes. Multiple radio telescopes spread over large distances (1 km to 5 000 km or more) are now used in concert to mimic a single large telescope with angular resolutions down to better than $0.001''$ (arcseconds).

The Very Large Array (VLA) of 27 large radio telescopes extending over about 40 km of New Mexico desert operates on this principle. With its large area it has excellent sensitivity. It has produced many beautiful images of radio objects in the sky with angular resolution comparable to that of ground-based optical astronomy ($\sim 1''$).

The atmosphere of the earth is a great impediment to many kinds of astronomy. Photons over large bands of frequencies can not penetrate it. The advent of space vehicles from which observations could be made opened up the field of *x-ray astronomy*. Like radio astronomy, this field led to the discovery of a variety of new phenomena, such as neutron stars in orbit with ordinary nuclear-burning stars, high-temperature shock waves in supernova remnants, black holes (described below), and high-energy phenomena in distant quasars.

Space vehicles have also made possible the study of the *ultraviolet radiation* from nearby stars and distant galaxies and *gamma-ray emission* from pulsars and from the nuclei of active galaxies. *Infrared astronomy* can be carried out at only a few frequencies from the ground, but in space a wide band of frequencies are accessible. Infrared astronomers can peer into dust and gas clouds to detect newly formed stars. Space vehicles also carry optical/ultraviolet telescopes above the atmosphere to provide very high angular resolutions, $\lesssim 0.05''$ compared to the $\sim 1''$ normally attained below the atmosphere. This is a major feature of the Hubble Space Telescope.

The space program also has provided a platform for *in situ* observations of the planets and their satellites (moons); the spacecraft carries instruments to the near vicinity of the planet. These missions carry out a diversity of studies in a number of wavebands (radio through the ultraviolet) as well as magnetic, cosmic-ray, and plasma studies. The Voyager missions visited Jupiter, Saturn, Uranus and Neptune. One of them will soon leave the solar-system *heliosphere* and thus be able to carry out direct measurements of the *interstellar medium.*

A given celestial object can often be studied in several of the frequency domains from the radio to gamma rays. Each provides complementary information about the object. For example, the x rays provide information about very hot regions ($\sim$10 million kelvin) while infrared radiation reflects temperatures of a few thousand degrees or less. The use of all this information together is a powerful way to determine the underlying nature of a class of celestial objects. This type of research has come to be known as *multi-frequency astronomy.* Sky maps at various frequencies (cover illustrations) illustrate the variation of the character of the sky with frequency.

Signals other than the electromagnetic waves also provide information about the cosmos. Direct studies of *cosmic rays* (energetic protons, helium nuclei, etc.) circulating in the vast spaces between the stars are carried out at sea level and also from space. These high-energy particles were probably accelerated to such energies, at least in part, by the shock waves of supernova explosions.

Neutrinos, neutral quanta that interact very weakly with other matter, have been detected from the nuclear reactions in the center of the sun and from the spectacular implosion of a star in the Large Magellanic Cloud, an easily visible stellar system in the southern sky. The outburst is known as *supernova 1987A*. Neutrino detectors are placed underground to minimize background.

The detection of gravitational waves predicted by the theory of general relativity is still a challenge. Observatories to search for them with high sensitivity are now beginning operations, such as the US Laser Interferometer Gravitational-wave Observatory (LIGO) with interferometer “antennas” in Washington State and Louisiana or the German–UK GEO-600. A likely candidate source of gravitational waves is a binary system of two neutron stars in the last stages of spiraling into each other to form a black hole.

1.4 Interplay of observation and theory

The objective of astronomical studies is to learn about the nature of the celestial objects, including their sizes, masses, constituents, and the basic physical processes that take place within or near them. Progress is made through an interplay of observational data and theoretical insight. Observations guide the theorist and theories suggest observations. The pace of this interplay greatly accelerated in the late nineteenth and twentieth centuries due to the rapid increase in technical capability described above. The recent history of astronomy is replete with examples of this symbiosis of observation and theory.

Stars and nebulae

Dark absorption lines were discovered in the solar spectrum in 1802, and Joseph Fraunhofer (1787–1826) recorded the locations of about 600 of them. Comparison to spectra emitted by gases and solids in earth laboratories showed that the gaseous outer layer of the sun contains elements well known on earth. The quantum theory developed in the 1920s yields the frequencies of radiation emitted by atoms as well as the probabilities of emission under various conditions of density and temperature. This allowed astronomers to diagnose the conditions in the solar atmosphere and in the atmospheres of other more distant “suns”, the stars in the sky.

The light from the surface of our sun does not show us directly what is happening inside it. However, we now know that the energy source of the sun is nuclear fusion, a concept developed and demonstrated by nuclear physicists. Hydrogen nuclei under high pressures and temperatures fuse to become helium nuclei and other heavier elements. Theoretical models of stars that incorporate a nuclear energy source closely match the observed characteristics of real stars. This understanding has been verified by the measurement of neutrino fluxes from the sun as mentioned above; also see below.

In 1862, a faint companion star to Sirius was first seen with the aid of a new, large (0.46-m) telescope. Observations much later showed it to be very compact, about the size of the earth, but about 350 000 times more massive than the earth (about as massive as the sun). It was called a *white dwarf*. It was thought that the huge inward pull of gravity of such a compact object would prevent it from remaining stable at its observed size. (In a normal star like the sun, the pressure due to the hot gases prevents such a collapse.) In the mid 1920s, the newly developed quantum theory showed that *electron degeneracy pressure* would support such a star from further collapse, thus providing a physical basis for the existence of white dwarfs. Degeneracy pressure is strictly a quantum mechanical effect for which there is no classical analog.

Nuclear and quantum physics also led to the demonstration in 1939 that an extremely compact *neutron star* could be a stable state of matter. It would be about as massive as the sun, but $\sim$1000 times smaller than the white dwarf! It would be as dense as the nucleus of an atom and would consist almost solely of neutrons. (The high pressures within the star force the electrons to combine with the protons.) These stars were finally discovered in 1967, first as *radio pulsars*, and a few years later as *x-ray pulsars*. The neutron stars are typically spinning and shine in our direction once each rotation, as does a lighthouse beam. Their periods range from about 1 ms to about 1 ks (1000 s). This pulsing of the radiation gave them their name (“pulsars”). Note that, in this case, the underlying theory of neutron stars existed before their discovery, unlike the case of the white dwarf companion of Sirius where the observations spent decades in search of a theory.

These and other developments brought forward a general picture of the lives of stars. They form from the condensation of large gas and dust clouds in the interstellar medium that appear as beautiful colorful *nebula* such as the Trifid and Orion nebulae (Figs. 5, 6). A newly formed star stops shrinking and stabilizes when it becomes sufficiently dense and massive so that nuclear burning starts in its center.

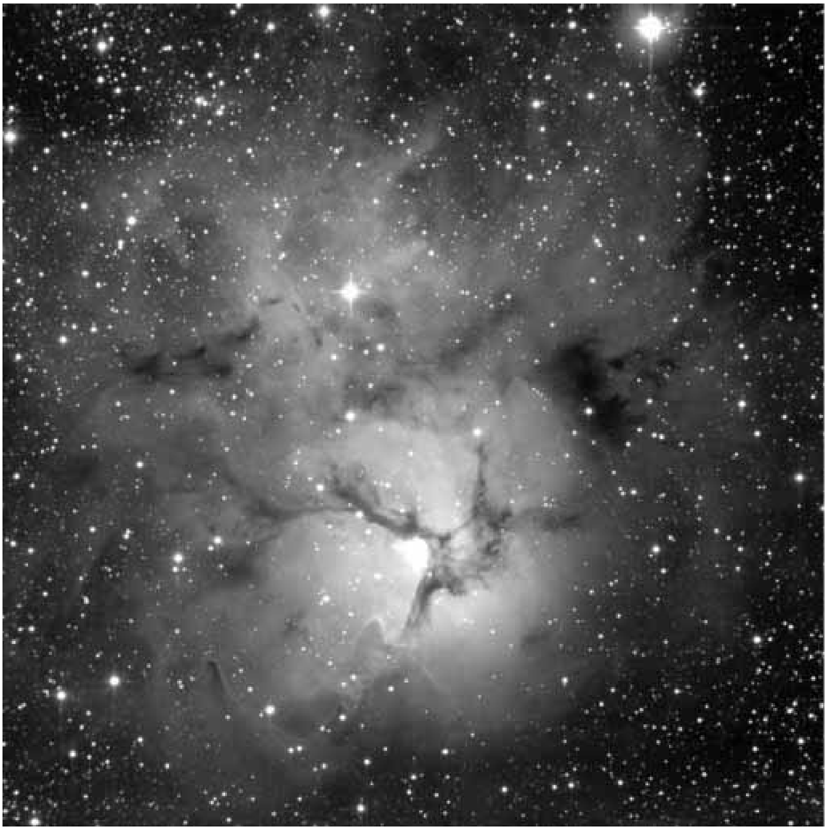


Figure 1.5. Trifid nebula, a star-formation region of gas and dust. Newly created hot massive stars radiate ultraviolet light that ionizes the surrounding gas which then emits radiation as it recombines. It is at distance 5500 LY and is 15′ in angular extent. The image is about 22′ square. North is up and east is left. [T. Boroson/NOAO/AURA/NSF]

Stars often form in groups of 10 or more; these groups are seen as *open clusters* of stars such as the Pleiades or "Seven Sisters" (Fig. 7). The more massive stars burn out quickly, in a few million years. Intermediate-mass stars like our sun live for ∼10 billion years, and lower mass stars would live longer than the age of the universe (10–20 billion years).

As the nuclear fuel in the star is expended, the star goes through several phases of size and color changes. It may expel a cloud of gas to become a beautiful *planetary nebula*. Radiation from the star excites the atoms in the expanding cloud so they fluoresce, as in the Ring nebula (Fig. 8). The star eventually becomes a compact object, a white dwarf or neutron star. The latter may occur by means of a spectacular supernova implosion/explosion to produce the Crab pulsar and nebula as noted above. If the original star is sufficiently massive, it could instead collapse

Figure 1.6. Orion nebula, a star formation region in the sword of Orion. The nebula is 1300 LY distant and of full optical extent 1.5°. Only the northern half is shown here. The famous trapezium stars are in the southern half. North is up and east is left. [Gary Bernstein, Regents U. Michigan, Lucent Technologies]

to become a *black hole*, an object so dense that a light beam can not escape from its gravitational pull. Observations and theory together point strongly toward the existence of black holes, but there is still room for more definitive evidence.

Galaxies and the universe

The fuzzy, irregular band of diffuse light that extends across the night sky is known as the Milky Way. Astronomers determined that this light consists of a dense collection of many isolated stars. The Milky Way was thus found to be a large "universe" of stars of which the sun is a member. It is called the *Galaxy* (with capital G)[1] after the

[1] We generally follow astronomical practice and use "the Galaxy" to describe the Milky Way system of stars. On occasion, we use "(MW) Galaxy" as a reminder where there could be confusion with other "galaxies".

(a) Pleiades (optical)

(b) Pleiades (x ray)

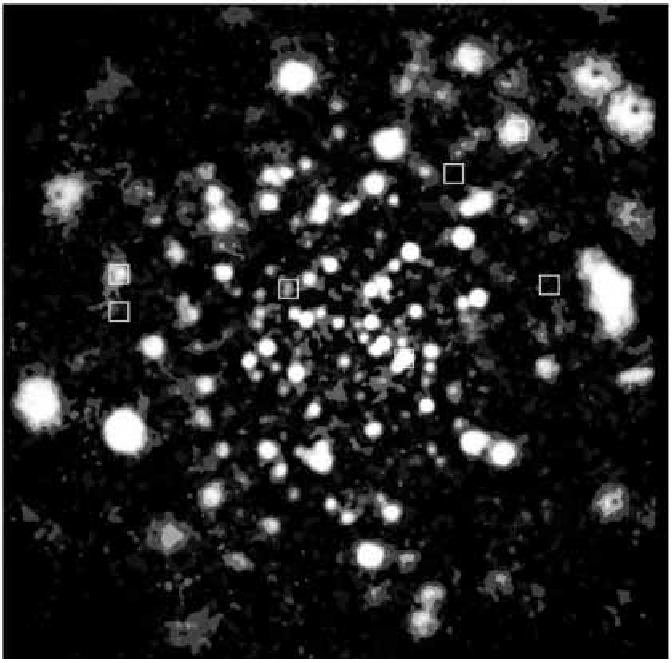


Figure 1.7. The Pleiades, or "Seven Sisters", an open cluster of $\sim$100 young stars in (a) optical light and (b) x rays. The haze in (a) is blue light scattered by dust in the cluster. The boxes in (b) indicate the positions of the brightest optical stars. The Pleiades are about 400 LY distant and about 2° in angular extent. North is up and east is left. [(a): © Anglo-Australian Obs./ Royal Obs., Edinburgh; photo from UK Schmidt plates by David Malin. (b) T. Preibisch (MPIfR), ROSAT Project, MPE, NASA]

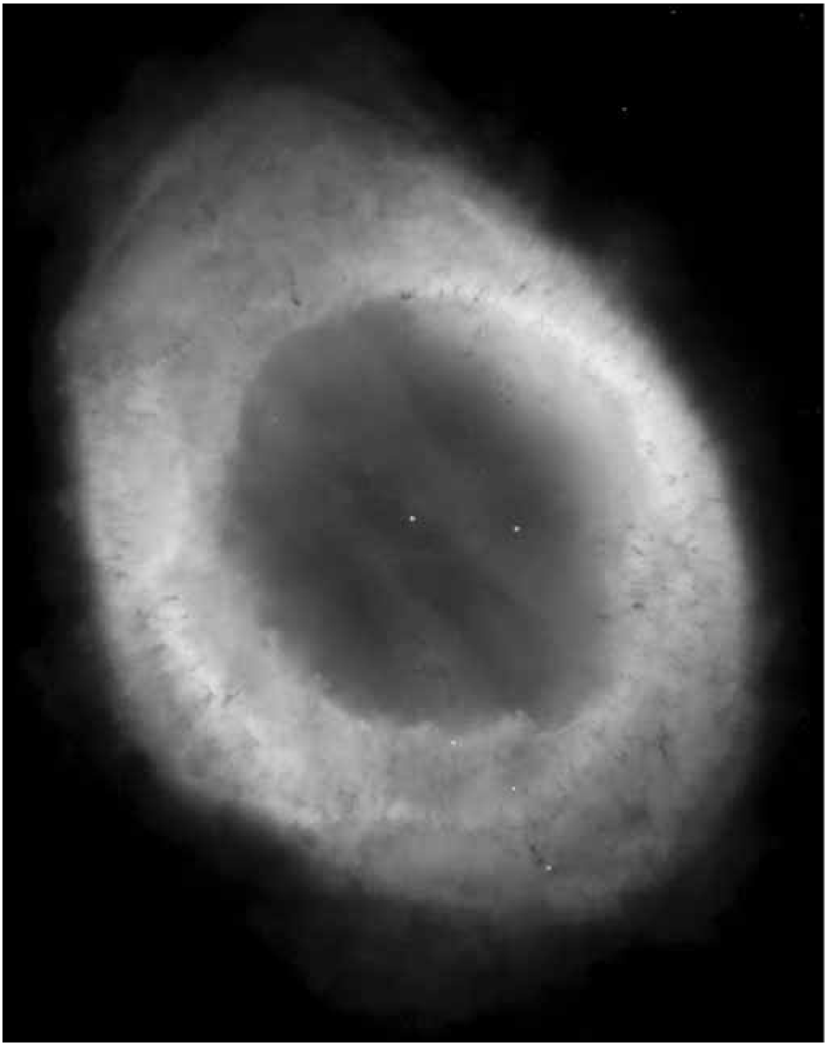


Figure 1.8. The Ring nebula, a planetary nebula. The central star in a late stage of its evolution has ejected gas which it fluoresces. It is about 2300 LY distant and 1.3′ in extent. [H. Bond *et al.*, Hubble Heritage Team (STScI/AURA)]

Greek word *gála* for "milk". It was in 1917 that Harlow Shapley determined the distance to the center of the Galaxy to be ~25 000 LY[1] (current value). He did this by measuring the locations and distances of *globular clusters* (tightly clustered groups of 10^5 or 10^6 old stars; Fig. 9), which he realized must surround the center

[1] One light year (LY) is the distance light travels in one year in a vacuum. It is not an SI unit, but we choose to use it because of its natural physical meaning. There are several definitions of the year (i.e. Tropical, Julian and Sidereal) which differ slightly in duration, but each is consistent with the conversion, 1.0 LY $= 0.946 \times 10^{16}$ m $\approx 1 \times 10^{16}$ m. We use the symbol "yr" for the generic year of ~365.25 d where "d" is the non-SI unit for the mean solar day which is about equal to 86 400 SI (atomic) seconds. See Chapter 4.

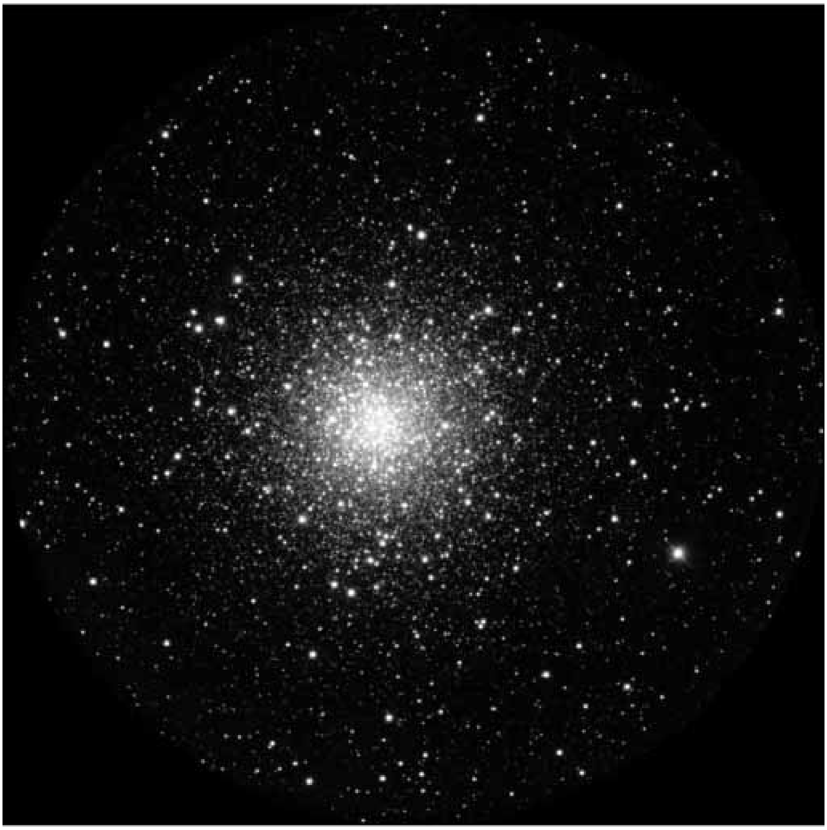


Figure 1.9. The globular cluster, M10. Globular clusters are remnants from the formation of galaxies. There are about 160 associated with the (MW) Galaxy. Each contains 10^5 to 10^6 stars and orbits the center of the Galaxy. M10 is about 65 000 LY from the center of the Galaxy. This photo is 26′ full width; the cluster is about 69′ in diameter. North is up and east is left. [T. Credner & S. Kohle, Hoher List Observatory]

of the Galaxy. The discus-shaped Galaxy has a diameter of roughly 100 000 LY. It contains about 10^{11} stars.

The nature of certain diffuse nebulae of small angular extent in the sky was hotly debated: were they diffuse clouds of gas within the Galaxy or were they very distant giant *galaxies* (with lower case *g*) similar to the Galaxy? Edwin Hubble obtained a distance to the *Andromeda nebula* (Fig. 10) in 1924 which turned out to be very large – the current value is 2.5 million light years – which placed the nebula well outside the Galaxy. This distance and its apparent angular size on the sky ($\sim$3.4°) demonstrated that Andromeda is another huge galaxy like the Milky Way, of size $\sim$100 000 LY.

Figure 1.10. Andromeda nebula M31, our sister galaxy, is about 2.0° in angular extent and is distant 2.5×10^6 light years. North is 26° counterclockwise (left) of "up", and east is 90° further ccw, toward the lower left. [Jason Ware]

Galaxies are found out to great distances; more than 10^{11} galaxies (or precursor galaxy fragments) are in principle detectable with the Hubble Space Telescope. Some have cores that emit intense radiation at many wavebands. These *active galactic nuclei* (AGN) may be powered by a massive black hole of mass $\sim 10^8$ solar masses. The most luminous of these cores are known as quasars; they can now be detected to great distances, up to ~90% the distance to the "edge of the observable universe", about 12 billion light years distant.

A great theoretical advance was Albert Einstein's *general theory of relativity* (1916). This provided a dynamical description of motions in space-time that allowed for accelerating (non-inertial) frames of reference. In this context, gravity can be viewed as a distortion of space. One consequence of this theory is that light rays from a distant star should bend as they pass through a gravitational field, i.e., near a star or galaxy. This effect and its magnitude were first measured in 1919 during a solar eclipse; it made Einstein famous. With more powerful telescopes, *gravitational lensing* is found to be a prevalent phenomenon in the sky. Distant quasars are sometimes seen as double images or as narrow crescents because an intervening galaxy or group of galaxies serves as a gravitational lens. General relativity also predicts the existence of black holes.

Another consequence of Einstein's theory is that the universe as a whole should evolve. It is expected to be expanding and slowing, or instead, it could be contracting

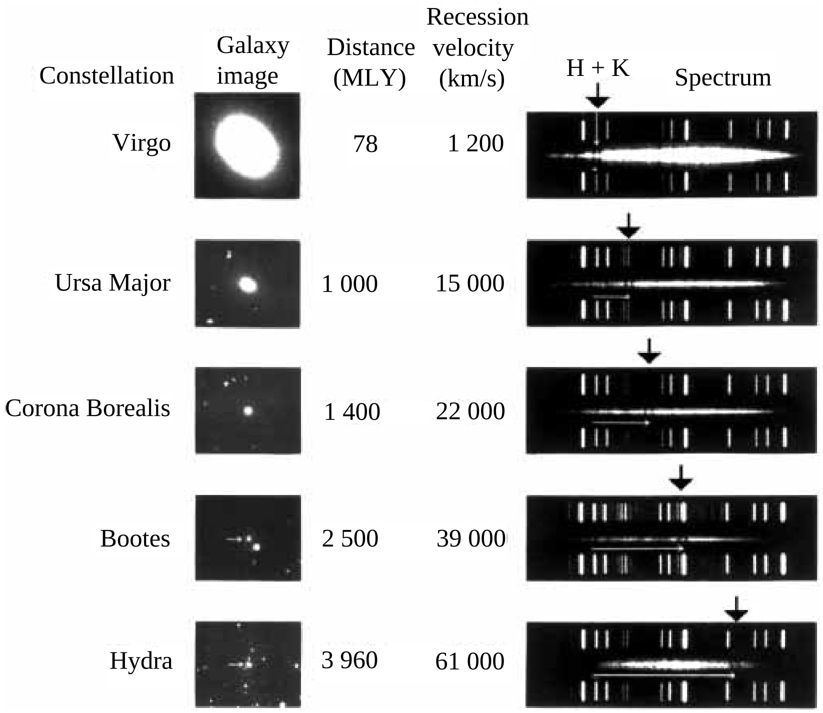


Figure 1.11. Images and spectra of distant galaxies (nebulae). The fainter (and hence more distant) objects show the double absorption (dark) H and K lines of ionized calcium shifted to longer and longer wavelengths, i.e., to the red. If the redshift is interpreted as a Doppler shift, this would indicate a correlation between recession velocity and distance (See Chapter 9). More properly stated, the redshifts are due to the effect of an expanding universe on photons from the distant galaxy as they travel to the earth. *Redshift* is defined as the fractional wavelength shift, $z \equiv (\lambda_{obs} - \lambda_0)/\lambda_0$ where λ_{obs} and λ_0 are the observed and rest wavelengths respectively. The redshifts are given here in terms of the equivalent velocities. For speeds much less than the speed of light, these are the Doppler velocities, cz. The distances to the galaxies are derived from the redshift assuming a velocity/distance ratio (Hubble constant) of 15.3 km/s per mega light year. [Palomar Observatory/ Caltech]

and speeding up. The analog is a ball in the earth's gravitational field: it rises and slows, or it falls and speeds up; it does not remain motionless. This aspect of the theory was not appreciated until *after* Edwin Hubble's observations of distant galaxies showed in 1929 that, indeed, galaxies are receding from one another (Fig. 11); the universe is expanding! This expansion is similar to that of a raisin bread baking in an oven; every raisin moves away from its neighbors as the bread rises. In the universe, the galaxies are like the raisins. This discovery opened up the entire field of cosmology: the story of the birth, life, and death of our universe.

There is strong evidence that the universe was once hot and dense, some $\sim$10 billion years ago. Such a beginning is often called the *big bang*. The proportions of light elements (Li, Be, He) in the solar system and Galaxy relative to hydrogen are nicely consistent with those expected from nuclear interactions in the hot early universe. Also, a diffuse radiation at microwave frequencies is seen to arrive from all directions of the sky. It is known as the cosmic microwave background radiation, CMB, and has a blackbody spectrum with temperature 2.7 K. This radiation is expected theoretically to be the remnant of the early hot phases, and its characteristics match the theory extraordinarily well. Also geological information yields ages of rocks and meteorites that are comparable to 10^{10} years, an age inferred independently from the expansion of the galaxies.

The final fate of the universe is not known. According to viable theories, it could expand forever, it could slow to a stop and start contracting, or it could be in between, slowing "critically" forever. Continuing interplay of observation and theory are providing further progress on this issue; see below.

New horizons

Another consequence of the general theory of relativity is that oscillating masses should radiate gravitational waves. (Recall that oscillating electric charges radiate electromagnetic waves.) A *binary radio pulsar* can consist of two neutron stars in orbit about their common center of mass. If they radiate away enough energy through gravitational radiation, they will move closer together as they orbit around their common center of mass. In so doing they lose potential energy and gain a lesser amount of kinetic energy. At this writing, the rates of decay of several such systems, including PSR 1913 + 16 (the *Hulse–Taylor pulsar*) and PSR 1534 + 12, confirm to very high precision the predictions of Einstein's general relativity. There are efforts underway to detect gravitational waves directly as mentioned above. Very sensitive and large detection systems are required due to the small amplitude of the expected signals.

The physics of the interior of the sun may not be completely resolved. The neutrino experiments mentioned above do not show the expected numbers of neutrinos; the observed rate is about half that expected. The neutrinos are a measure of the nuclear reactions taking place within the sun. Are the conditions of temperature, density, and composition in the nuclear-burning regions of the sun not well understood? Are the neutrinos changing form (*neutrino oscillations*) as they pass through the solar material so some of them become undetectable in existing instruments? Neutrino oscillations of a different type of neutrino (the *muon neutrino*) have been detected in the flux of neutrinos created by cosmic ray interactions in the earth's atmosphere. This is a major advance in neutrino physics. The resolution of the solar neutrino puzzle has important ramifications in astrophysics and particle physics, and ongoing experiments are addressing it.

There is a well-received theory of the early universe (the *inflationary universe*) wherein it expanded by many orders of magnitude very early, 10^{-33} s, after the "big bang". This suggests the universe is now expanding at just the *critical* rate where it asymptotically approaches zero expansion speed; it neither completely "escapes", nor does it start falling inward. A major difficulty with this view is that the visible matter in the universe falls far short of the mass required to yield the critical condition.

If the theory is correct, there must be some new kind of *dark matter* of an unknown type. Such speculation gains credence from the motions of stars in galaxies and of galaxies in *clusters of galaxies*. In both cases, the objects move so rapidly in a confined volume that unseen matter would seem to be holding them in their orbits. The nature of this dark matter is one of the great questions now facing astrophysicists. The picture is further complicated by indications from observations of supernovae that the expansion of the universe is increasing, due to some (unknown) type of *dark energy*.

The distribution of galaxies in space is found to be very clumpy with huge voids and "walls" of galaxies. This can be compared to the very smooth distribution of the CMB. It is generally believed that the galaxy clustering arises from small density fluctuations in the early universe, and these should be visible as tiny fluctuations in the brightness (temperature) of the CMB as a function of angle on the sky. In fact, such fluctuations have been detected by the Cosmic Background Explorer (COBE) and WMAP satellites, and with experiments carried out in Antarctica (high-altitude balloon and ground based). These warm and cool spots and the postulated existence of large amounts of *cold dark matter* could well lead to the formation of galaxies with the observed clustering. The dominant angular scale of the CMB fluctuations, $\sim 1^\circ$, indicates that the universe is expanding at the critical rate, or equivalently that it has a "flat" geometry. This gives support to the existence of an episode of inflation in the early universe. Confidence in these ideas is growing at this writing.

These are only some of the challenges facing astronomers today. The nature of gamma-ray bursts, the most energetic explosions known to man, and the mechanisms that give rise to jets of material from many different types of celestial objects are among them. If the past has been any indication, some of the answers will prove to be quite surprising. Also serendipitous discoveries will surely provide new surprises and new questions. It is likely that many of the questions asked today will be shown to be off the mark. The truth will lie in other unexpected directions.

Problems

There are no problems assigned for this chapter. However, two problems in Chapter 9 (9.51 and 9.52) illustrate the methods the ancients used as described here. The student may wish to attempt these now.